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USE OF FALLOUT Pb-210 MEASUREMENTS TO INVESTIGATE LONGER-TERM RATES AND PATTERNS OF OVERBANK SEDIMENT DEPOSITION ON THE FLOODPLAINS OF LOWLAND RIVERS

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ABSTRACT

The potential for using fallout (unsupported) Pb-210 (^{210}Pb) measurements to estimate rates of overbank sediment deposition on the floodplains of lowland rivers is explored. A model which distinguishes the contribution from direct atmospheric fallout and the catchment-derived input associated with the deposition of suspended sediment has been developed to interpret the fallout Pb-210 inventories at floodplain sampling sites and to estimate average sediment accumulation rates over the past 100 years. The approach has been successfully used to estimate rates of overbank sedimentation on the floodplains of the Rivers Culm and Exe in Devon, U.K. A detailed investigation of the pattern of longer-term sedimentation rates within a small reach of the floodplain of the River Culm indicated a range of deposition rates between 0·07 and 0·59 $g\,cm^{-2}\,a^{-1}$, which was in close agreement with estimates of current sedimentation rates obtained using sedimentation traps.

KEY WORDS river floodplains; lowland rivers; overbank sedimentation; suspended sediment; Pb-210 measurements

INTRODUCTION

Overbank sedimentation on the floodplains of lowland rivers during flood events represents an important component of their geomorphology and evolution (Wolman and Leopold, 1957; Lewin, 1978; Macklin and Lewin, 1993). Such deposition can also represent a significant conveyance loss in the transfer of sediment through river systems and is therefore often a key component of catchment sediment budgets (Lambert and Walling, 1987; Walling and Quine, 1993). Furthermore, the close affinity of fine sediment for many contaminants, such as heavy metals and pesticides, means that overbank sediment deposits can represent important long-term sinks for such contaminants (Marron, 1992; Macklin *et al.*, 1994; Rang and Schouten, 1989). Against this background, there is an increasing need for information on contemporary rates of overbank deposition and the spatial patterns involved. Such information is required to improve our understanding of the contemporary geomorphological evolution of floodplains, to evaluate their significance as sediment sinks and to predict the fate of sediment-associated nutrients and contaminants transported through river systems. Furthermore, there is also a need to verify existing models of floodplain sedimentation and to test their assumptions against field data (James, 1985; Marriott, 1992).

Any attempt to document contemporary or recent rates of overbank sediment deposition on river floodplains faces many practical and conceptual problems. Overbank flood events occur only infrequently and the associated deposition processes are characterized by substantial temporal and spatial variability, which in turn introduces significant sampling problems. Existing approaches to documenting contemporary or recent rates of overbank deposition on floodplains effectively fall into two groups, based primary on the timescale involved. The first group represents approaches that are essentially event-based and attempt to measure the

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deposition associated with individual floods. These include the use of sediment traps (e.g. Gretener and Strömquist, 1987; Lambert and Walling, 1987) and post-event surveys of sediment deposits aimed at determining their depth and distribution (Brown, 1983; Kesel *et al.*, 1974; Marriott, 1992). Both introduce significant problems which include restrictions on the sampling densities that can be realistically employed and the difficulty of measuring low rates of deposition. The second group of approaches produces estimates of deposition rates averaged over a number of years and relies on establishing the date of a particular level within the deposit and calculating the rate of deposition from the depth of material overlying this level. Methods used to define levels of known date include prior benchmark surveys (e.g. Happ, 1968; Leopold, 1973), the existence of datable surfaces or material (e.g. Costa, 1975), linking trace metal profiles to the chronology of mining activity in the upstream catchment (e.g. Lewin and Macklin, 1987) and the use of the bomb-derived fallout radionuclide Cs-137, which provides a means of estimating sedimentation rates during the period since the commencement of bomb tests in the early 1950s (e.g. Ritchie *et al.*, 1975; Walling and Bradley, 1989; Walling *et al.*, 1992a). The use of Cs-137 possesses particular advantages in terms of its widespread applicability and lack of reliance on particular local conditions, the potential for assembling information on rates of sedimentation for a large number of points on the floodplain, and the medium-term timescales involved.

In essence, the Cs-137 technique involves either evaluating the shape of the Cs-137 profile in the sediment or, alternatively, apportioning the Cs-137 inventory at a sampling location on a floodplain into a direct atmospheric fallout component and a catchment-derived Cs-137 component associated with deposition of suspended sediment eroded from the upstream drainage basin and transported by the river. In the former case, the depth at which the peak Cs-137 concentration occurs can be related to the period of peak fallout in 1963, while in the latter case the estimate of the catchment-derived contribution to the total Cs-137 inventory can be used to estimate the depth of sediment accumulation at the sampling location (Walling *et al.*, 1992a; Walling and He, 1992, 1993). As noted above, particular advantages of the Cs-137 approach include the possibility of obtaining retrospective estimates of medium-term (*c.* 35 years) rates of floodplain sedimentation on the basis of a single site visit and of assembling data with a high spatial resolution capable of representing the spatial patterns involved.

The study reported in this paper explores the potential application of another fallout radionuclide, namely Pb-210 (^{210}Pb), in investigating longer-term (*c.* 100 years) rates of floodplain sedimentation. Pb-210 is an end product of the U-238 (^{238}U) decay series with a half-life of 22·2 years, and its presence in the atmosphere is due to the diffusion of Rn-222 (^{222}Rn, daughter of Ra-226 or ^{226}Ra) from the lithosphere into the atmosphere and its subsequent decay. As in the case of Cs-137, deposition of Pb-210 from the atmosphere to the land surface is primarily associated with wet fallout in association with precipitation (Nozaki *et al.*, 1978; Nevissi, 1985). However, whereas Cs-137 fallout has varied through time and occurred primarily in the late 1950s and 1960s as a result of nuclear weapons testing, Pb-210 fallout represents an essentially natural process and can be viewed as having been effectively uniform through time. Fallout Pb-210 is commonly designated unsupported Pb-210 when incorporated into soils or sediments, in order to distinguish it from the *in situ* Pb-210 produced by the decay of Ra-226. It is this unsupported component of Pb-210 in sediment that offers potential for use in estimating floodplain sedimentation rates. As in the case of Cs-137, the total inventory of unsupported Pb-210 in a floodplain sediment core reflects both the direct atmospheric fallout flux of the radionuclide to the floodplain surface and its deposition during overbank flooding in association with suspended sediment mobilized from the upstream catchment by erosion (Walling and He, 1992, 1993).

Although Pb-210 has been successfully used as a basis for establishing lake sediment chronologies over the past 100–150 years through application of the CFCS (constant flux and constant sedimentation rate), CIC (constant initial concentration) and CRS (constant rate of supply) Pb-210 dating models (Appleby and Oldfield, 1978; Robbins, 1978; Oldfield and Appleby, 1984a, b), its use for establishing the chronology of floodplain deposits is more complicated. The concepts involved in Pb-210 dating models for lake sediments remain generally applicable for the floodplains of lowland rivers which can be assumed to be characterized by quasi-continuous sedimentation, but a number of additional factors need to be taken into consideration. One important difference in the distribution of unsupported Pb-210 between lake and floodplain sediments is that whereas the annual input of direct atmospheric fallout Pb-210 to a lake is commonly assumed to be

contained within the sediment deposited during that year, in the case of a floodplain it will be distributed approximately exponentially with depth in the surface horizon of the existing floodplain sediment, which may itself be buried by further accretion during individual flood events (He, 1993). As a result, neither the CFCS model used for Pb-210 dating of lake sediments, which assumes a constant unsupported Pb-210 input and a constant sedimentation rate, nor the CIC model (constant initial concentration of unsupported Pb-210 in deposited sediment) may be applicable to floodplain sediments. Neither model is strictly applicable if the annual sedimentation rate is not substantially greater than the depth of penetration of the annual fallout input represented by the cumulative relaxation mass depth of the initial fallout distribution (defined as the mass depth from the floodplain surface where the concentration of Pb-210 in sediment is $1/e$ that of the concentration in sediment at the surface), because both models assume that the annual input of unsupported Pb-210 will be retained within the sediment deposited during that year (Oldfield and Appleby, 1984a, b). Furthermore, in most situations, total unsupported Pb-210 inventories will be significantly greater than the local fallout reference level (the direct atmospheric input), indicating that catchment-derived inputs are important. The deposition of unsupported Pb-210 in association with suspended sediment mobilized from the upstream catchment can be expected to vary through time in response to the magnitude and timing of overbank flood events, and neither annual inputs of unsupported Pb-210 to the sediment nor annual sedimentation rates can be assumed to be constant. Differences in the annual amount of deposited sediment will be associated with different annual contributions of sediment-associated unsupported Pb-210 to the overall inventory, and both the CFCS and CRS dating models will therefore be inappropriate. Post-depositional remobilization of sediment and/or of Pb-210 itself may further complicate the distribution of fallout Pb-210 in floodplain sediments.

In spite of the difficulties outlined above, the distribution of unsupported Pb-210 in floodplain sediments and the associated inventories may still afford a basis for deriving information about rates of floodplain sedimentation. For example, if sediment mixing is minimal, and the depth increments for a sectioned sediment core are greater than the annual sedimentation rate and the relaxation cumulative mass of the initial Pb-210 distribution associated with direct atmospheric fallout, and a constant sedimentation rate can be assumed, the CFCS model may still be applied. In situations where the total excess Pb-210 inventory is close to the local reference level and deposited sediment is therefore associated with low levels of unsupported Pb-210, the CRS lake Pb-210 dating model may be applicable.

Because the direct atmospheric fallout input of Pb-210 to a floodplain surface can be assumed to be essentially uniform spatially and subject to minimal post-depositional lateral redistribution, it can be estimated from the local reference inventory. The excess unsupported Pb-210 inventory for a particular point on the floodplain surface can thus be calculated as the total unsupported Pb-210 inventory less the direct atmospheric-derived or fallout inventory for the location. This excess unsupported Pb-210 inventory can be assumed to be derived solely from the catchment through deposition of transported sediment. This situation differs from that encountered in lakes, where the magnitude of the direct atmospheric fallout contribution to the unsupported Pb-210 inventory at a particular location on the lake bed can exhibit significant spatial variation due to sediment focusing. The excess unsupported Pb-210 inventory associated with a floodplain sediment core may in turn be used to estimate the long-term average sedimentation rate, if the behaviour of unsupported Pb-210 in suspended sediment and deposited sediment, including its concentration and the influence of grain size on its association with sediment particles, is known. This approach, which will be discussed in the following section, has been used by the authors to investigate rates and patterns of overbank sedimentation on the floodplains of the Rivers Culm and Exe in Devon, U.K., over the last 100 years.

A CATCHMENT-RELATED Pb-210 FLOODPLAIN SEDIMENT DATING MODEL

As noted above, the input of unsupported Pb-210 to a depositional location on a floodplain will commonly comprise contributions from two sources, namely, direct atmospheric fallout associated with precipitation, and a catchment-derived input associated with suspended sediment deposited during overbank flood events. The total input flux of unsupported Pb-210 $I_{in}(t')$ ($\mathrm{mBq\,cm^{-2}a^{-1}}$) to a deposition site at time t'(a) may

therefore be expressed as:

$$I_{\text{in}}(t') = I_{\text{At}}(t') + RC_{\text{r}}(t') \tag{1}$$

where $I_{\text{At}}(t')$ = local atmospheric Pb-210 fallout flux (mBq cm^{-2}a^{-1}); R = sedimentation rate (g cm^{-2}a^{-1}); $C_{\text{r}}(t')$ = unsupported Pb-210 concentration in catchment-derived sediment (mBq g^{-1}). The second term on the right-hand side of Equation 1 represents the input of the catchment-derived unsupported Pb-210 associated with deposition of fluvial suspended sediment and can be viewed as representing the excess unsupported Pb-210 inventory. Both R and $C_{\text{r}}(t')$ are site-specific parameters, which, for example, reflect the spatial variation of sediment deposition rates on the floodplain induced by the dynamic behaviour of sedimentation, and the grain size composition of the deposited sediment. Sediment with a finer grain size composition will be characterized by higher unsupported Pb-210 concentrations than coarser sediment deposited at a different location during the same storm event, because of the preferential association of fallout Pb-210 with the fine fractions. Since the suspended sediment transported by a river represents a mixture of sediment derived from a range of sources characterized by different unsupported Pb-210 levels, its unsupported Pb-210 concentration will also reflect the relative importance of the different sources.

While the catchment-derived unsupported Pb-210 input can reasonably be assumed to be uniformly distributed in the sediment deposited during a specific event, the atmosphere-derived component, which arrives as fallout to the floodplain surface, will be incorporated into the upper horizons of the existing sediment profile. Sediment mixing caused by soil fauna will further redistribute the unsupported Pb-210 derived from both sources within the sediment profile. In order to overcome uncertainties associated with the initial distribution of the atmospheric fallout Pb-210 in the accumulating sediment and with post-depositional mixing of sediment, the following approach to estimating the rates of floodplain sedimentation has been adopted. This involves using the excess unsupported Pb-210 inventory for the sediment profile and the concentrations of unsupported Pb-210 in deposited sediment or in fluvial suspended sediment to estimate the sedimentation rate at a specific point on a floodplain. From Equation 1, the total unsupported Pb-210 A_{inv}(mBq cm^{-2}) measured for a specific point on a floodplain can be represented by the following equation when deposition has existed for over 100 years (about five times the half-life of Pb-210):

$$A_{\text{inv}} = \int_0^{\infty} I_{\text{in}}(t')\mathrm{e}^{-\lambda_{\text{Pb}}t'}\mathrm{d}t' = A_{\text{inv,At}} + A_{\text{ca}} \tag{2}$$

where λ_{Pb} = decay constant of Pb-210 (a^{-1}); $A_{\text{inv,At}}$ = local fallout Pb-210 inventory (mBq cm^{-2}); A_{ca} = excess unsupported Pb-210 inventory derived from the catchment (mBq cm^{-2}). The local fallout Pb-210 inventory can be measured by analysing soil samples collected from undisturbed land close to the floodplain above the inundation level. From Equation 1, A_{ca} can be calculated from the sedimentation rate R and the concentration of catchment-derived unsupported Pb-210 in deposited sediment C_{r}:

$$A_{\text{ca}} = \int_0^{\infty} R(t')C_{\text{r}}(t')\mathrm{e}^{-\lambda_{\text{Pb}}t'}\mathrm{d}t' \tag{3}$$

Both the sedimentation rate R and unsupported Pb-210 concentration C_{r} in catchment-derived sediment can be expected to vary through time in response to the magnitude and frequency of flood events and changes in the relative proportions of sediment derived from individual sources. However, if both are represented by their long-term averages and are thus assumed to be constant through time, this corresponds to a constant initial concentration of unsupported Pb-210 in deposited sediment and a constant sedimentation rate, which may be termed the 'CICCS model', and Equation 3 reduces to:

$$A_{\text{ca}} = \frac{1}{\lambda_{\text{Pb}}} R\, C_{\text{r}} \tag{4}$$

From Equation 2, the catchment-derived (or excess) unsupported Pb-210 inventory in sediment can be calculated as the difference between the measured total unsupported Pb-210 inventory and the measured

local fallout input:

$$A_{ca} = A_{inv} - A_{inv,At} \tag{5}$$

From Equations 4 and 5, the sediment accumulation rate R at the deposition point can be estimated from the excess unsupported Pb-210 inventory and its initial concentration in deposited sediment derived from the catchment according to:

$$R = \lambda_{Pb} \frac{A_{inv} - A_{inv,At}}{C_r} \tag{6}$$

The advantage of using Equation 6 to estimate the sediment accumulation rate is that problems relating to uncertainties concerning the effects of the initial distribution of fallout Pb-210 and of post-depositional sediment mixing on the unsupported Pb-210 depth profile will be eliminated. Work associated with sample measurements will also be minimized, because analysis of a single representative subsample of a whole sediment core from a depositional site can be used to establish its total unsupported Pb-210 inventory, whereas measurements of over 20 samples are usually required to determine the depth profile of unsupported Pb-210 in a single core. However, it should be noted that, unlike the CIC and CRS models,the CICCS model can only give a linear age–depth relationship at a depositional location for floodplain sediment and that the sedimentation rate given by Equation 6 assumes quasi-continuous sedimentation and therefore represents the mean value over approximately the past 100 years, because it has been assumed to be constant in deriving the equation. This mean value may in some cases mask considerable inter-annual variation in deposition rates (Macklin *et al.*, 1992) and it must clearly be viewed as an *average* sedimentation rate. It should, however, be emphasized that this limitation will be common to most approaches to estimating longer-term rates of floodplain sedimentation based on datable levels and where the total deposition during a known period of time is documented. Furthermore, inspection of a representative unsupported Pb-210 depth profile for the site (Figure 2) can be used to check the general validity of the assumption of quasi-continuous sedimentation. Where quasi-continuous sedimentation has occurred, the unsupported Pb-210 profile will exhibit an essentially uniform reduction in concentration with depth. Where sedimentation has been highly sporadic and associated with relatively few major events producing highly variable depths of sedimentation, the profile will evidence discontinuities and a more stepped appearance. The assumption of a constant C_r also invokes the assumption that temporal variations in sediment sources and in sediment transport and sediment deposition processes have shown no major changes over the past 100 years. Again, this assumption can be verified in very general terms by inspection of a representative unsupported Pb-210 depth profile. An essentially uniform reduction in concentration with depth should be evident.

In order to use Equation 6 to determine sedimentation rate, the initial concentration of catchment-derived unsupported Pb-210, C_r, in deposited sediment must be known. The values of C_r may be determined directly, for example, by analysing samples collected using a sediment trap placed close to the sediment coring position. He (1993) has shown that levels of fallout Pb-210 in soils and sediments are influenced by the grain size distribution of the mineral component. This provides an alternative way to estimate C_r indirectly. If the concentration of unsupported Pb-210 in fluvial suspended sediment and in its individual grain size fractions is known, the concentration in deposited sediment can be estimated by taking account of its grain size composition:

$$C_r = \left(\frac{\bar{S}_r}{\bar{S}_f}\right)^{\nu} C_f \tag{7}$$

where C_f = mean unsupported Pb-210 concentration in fluvial sediment (mBq g^{-1}); $\bar{S}_r$ = specific surface area of deposited sediment ($m^2 g^{-1}$); $\bar{S}_f$ = mean specific surface area of fluvial suspended sediment ($m^2 g^{-1}$); ν = constant reflecting the partitioning of unsupported Pb-210 with different size fractions in sediment. The concentration of unsupported Pb-210 in deposited sediment contributed from the catchment may also be estimated by subtracting the direct fallout contribution from the total unsupported Pb-210 concentration in recently deposited sediment, if the atmosphere-derived contribution can be estimated. The CICCS

model outlined above has been used to investigate rates of sediment deposition on the floodplains of the Rivers Culm and Exe.

THE RIVER CULM AND RIVER EXE FLOODPLAINS

The River Exe has a total drainage area of *c.* 1500 km^2, and the River Culm, with a catchment area of *c.* 270 km^2, is one of its main tributaries (Figure 1). Flow gauging stations are maintained on both rivers by the National Rivers Authority and the University of Exeter, and bulk suspended sediment samples have been collected regularly from the rivers during flood events and analysed by the Department of Geography at the University of Exeter. Topographic, hydrological, geological and land-use conditions in the basins have been reported by a number of researchers (Walling and Kane, 1984; Lambert, 1986; Peart and Walling, 1988, Walling and Moorehead, 1989). The properties of suspended sediment transported by these rivers have also been investigated extensively by Walling (1978), Walling and Kane (1984), Walling and Bradley (1989), and Walling and Moorehead (1989). The lower reaches of both rivers are characterized by well-developed floodplains. Overbank sedimentation on the floodplain of the River Culm has been studied using several methods, including the deployment of sediment traps to collect overbank sediment deposits (Lambert, 1986; Walling and Bradley, 1989; Simm, 1993). Figure 1 shows the main drainage network of the Exe basin and the locations of the two floodplain sediment sampling sites on the River Culm near Silverton Mill and on the River Exe near Exeter.

SAMPLE COLLECTION, PREPARATION AND ANALYSIS

Sediment cores were collected from the two floodplain sites and from adjacent undisturbed permanent pasture above the level of the floodplain using a hand-operated motorized percussion corer. Cores were commonly 40 cm to 100 cm in length and care was taken to ensure that all sediment containing measurable unsupported Pb-210 was sampled. Cores were either sectioned into small depth increments (1 or 2 cm) for measuring the Pb-210 profile or, as in the majority of cases, bulked for measurement of the total unsupported Pb-210 inventory. Sediment traps were used to collect representative samples of overbank sediment deposits at the River Culm floodplain site, and suspended sediment samples were collected from both the rivers during flood events (see Lambert and Walling (1987), Walling and Bradley (1989) and Walling *et al.* (1992b) for a description of the relevent sampling methods). All samples were dried, ground and passed through a 2 mm sieve. The grain size distribution of the samples was measured using a MALVERN MasterSizer following standard chemical pretreatment. A γ-ray spectrometer was used to determine the Pb-210 and Ra-226 content of the samples simultaneously. Samples were sealed for 20 days before γ assay in order to ensure equilibrium between Ra-226 (half-life 1622 a) and Rn-222 (half-life 3·8 days). The γ-ray spectrometer comprises a high resolution, low background, low energy, high purity germanium coaxial detector (EG&G ORTEC LOAX HPGe) and a CANBERRA Series 35 PLUS amplifier and multichannel analyser. The Ra-226 activity in the samples was estimated from the measured activity of its short-lived daughter Pb-214 (^{214}Pb) which is also in equilibrium with Ra-226. The unsupported Pb-210 activity in the samples was calculated as the difference between the total Pb-210 activity and the Ra-226-supported Pb-210 activity (calculated from the activity of Ra-226 or Pb-214, (Joshi, 1987)). Samples were counted for *c.* 10 h, and for most of the samples this provides a measurement precision of $< \pm 10$ per cent (relative deviation) at a confidence level of 90 per cent (1·65 standard deviations) for the resulting values of Pb-210 and Pb-214 concentration.

TESTING THE APPROACH

Several sediment cores were collected from the two floodplain sites for Cs-137 and Pb-210 analysis. Two of the cores (one from each floodplain site) were selected to test the CICCS Pb-210 model. Figure 2 depicts the depth distribution of unsupported Pb-210 concentration in the two sediment profiles. The depth distribution of Cs-137 is shown for comparison. Analysis of soil cores collected from nearby stable and undisturbed

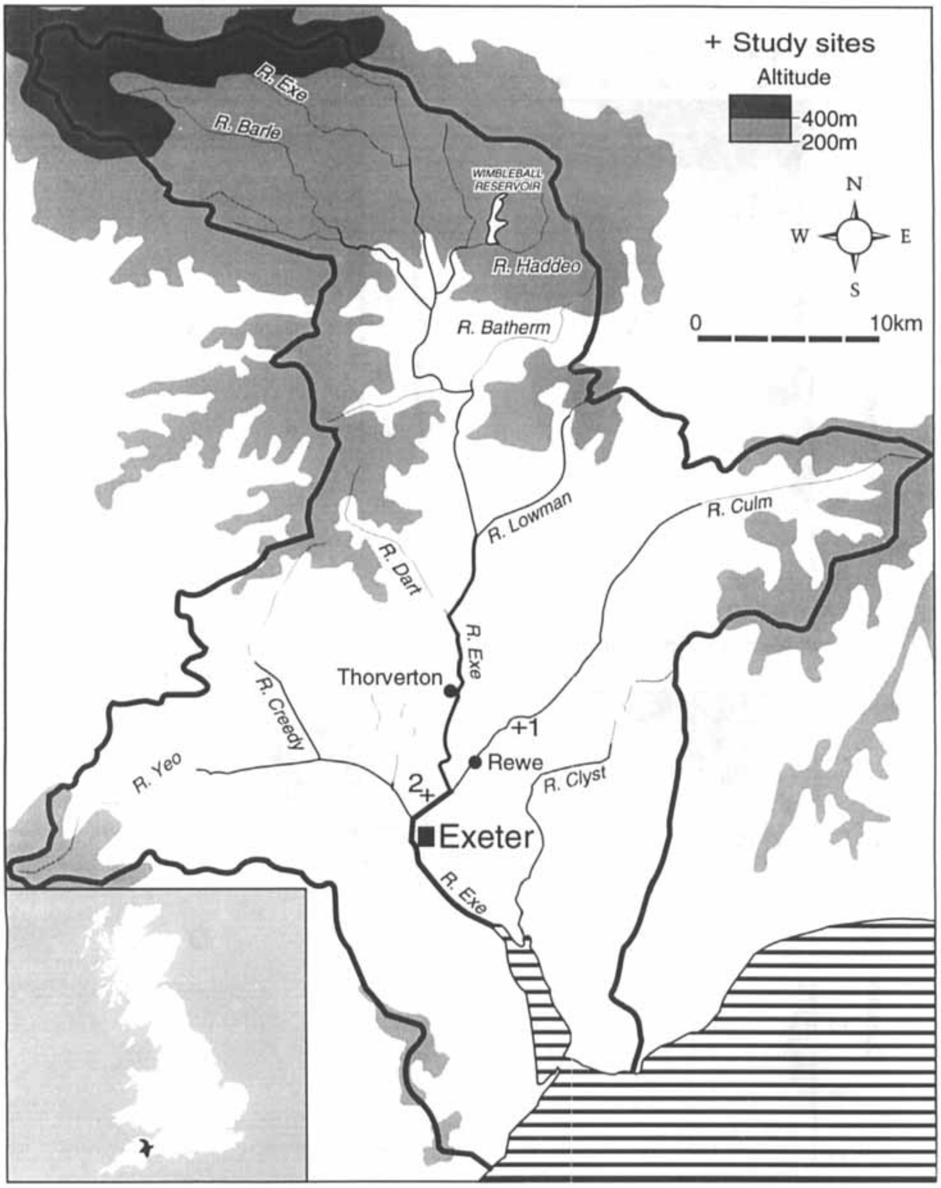

Figure 1. The drainage basin of the Rivers Exe and Culm showing the locations of the gauging stations at Rewe and Thorverton and of the two floodplain sediment sampling sites near Silverton Mill and Exeter

permanent pasture above the level of the floodplain indicates that the local direct atmospheric fallout inventory for unsupported Pb-210 is *c.* 300 mBq cm^{-2}. For the sediment core collected from the River Culm floodplain, the total unsupported Pb-210 inventory is 650 mBq cm^{-2}, and the catchment-derived unsupported Pb-210 is therefore *c.* 350 mBq cm^{-2}. Results from measurement of overbank deposits obtained using sediment traps at a point close to where the sediment core was taken over a period of two years show that the unsupported Pb-210 concentration in deposited sediment with a grain size distribution similar to that of surface sediment from the core averages about 34 mBq g^{-1}. Equation 6 provides an estimate of the mean sedimentation rate for this core of 0·32 g $cm^{-2}a^{-1}$. This value is close to 0·35 g $cm^{-2}a^{-1}$, the sedimentation rate estimated from its Cs-137 distribution using the method employed by Walling and He (1993). Both the values are consistent with the measurements of short-term deposition rates on the floodplain of the River

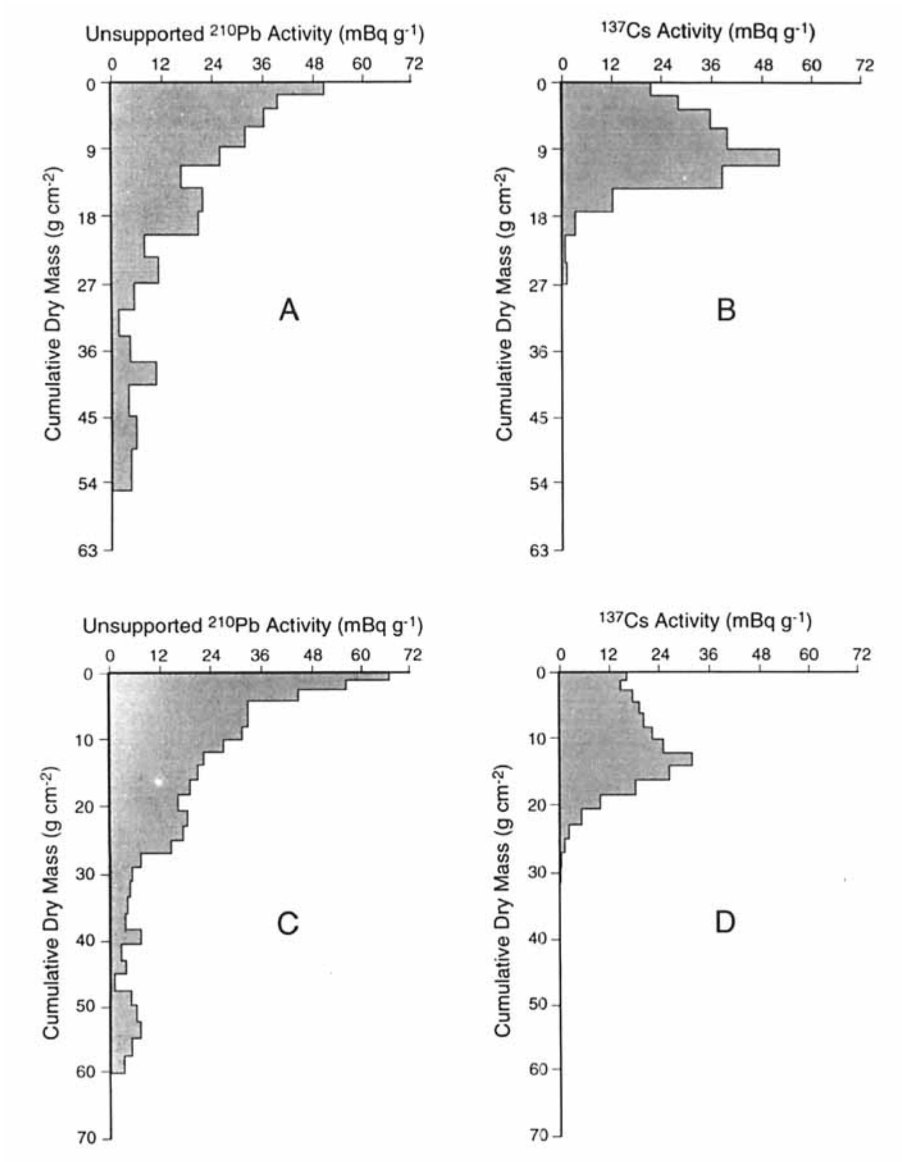

Figure 2. The unsupported Pb-210 and Cs-137 profiles for the two sediment cores collected from the Culm floodplain (A and B) and the Exe floodplain (C and D)

Culm undertaken by Simm (1993) using sedimentation traps. He documents a value of 0·31 $g\,cm^{-2}a^{-1}$ for a closed depression at Columbjohn, 4 km downstream, with similar characteristics to the site where the core was collected.

In the case of the sediment core collected from the River Exe floodplain, the catchment-derived unsupported Pb-210 inventory is estimated to be 600 $mBq\,cm^{-2}$. No sediment trap data were available for this site. The average unsupported Pb-210 concentration in suspended sediment collected from the upstream gauging station on the River Exe near Thorverton is *c.* 64 $mBq\,g^{-1}$. However, sediment deposited on the floodplain near Exeter comprises sediment from the River Exe and the River Culm. The mean unsupported Pb-210 concentration in suspended sediment collected from the gauging station on the River Culm at Rewe is *c.* 42 $mBq\,g^{-1}$. Walling and Kane (1984) estimate that the suspended sediment yield of the River Exe at

Thorverton (with an area of *c.* 500 km^2) is *c.* 25 t $km^{-2}a^{-1}$ and that of the River Culm at Rewe (with a catchment area of *c.* 270 km^2) is *c.* 40 t $km^{-2}a^{-1}$. This suggests a ratio of 1·37:1 for the sediment contribution from the two rivers to sediment carried by the river at this site. The unsupported Pb-210 concentration in suspended sediment transported by the River Exe near Exeter is thus estimated to be 55 mBq g^{-1}. A comparison of the grain size distribution of suspended sediment with that of overbank floodplain sediment indicates an enrichment ratio of *c.* 1·25 for unsupported Pb-210 concentrations in suspended sediment relative to floodplain deposits, and the initial unsupported Pb-210 concentration of deposited sediment in this core is therefore estimated to be 44 mBq g^{-1}. Using Equation 6, the mean sedimentation rate for this core is estimated to be 0·42 g $cm^{-2}a^{-1}$. The Cs-137 distribution for the same core gives an estimate of 0·45 g $cm^{-2}a^{-1}$. The age–depth relationships derived from the CICCS Pb-210 model (Equation 6) and a Cs-137 estimated age for the two cores are shown in Figure 3. The long-term sedimentation rates for the two cores estimated from the CICCS model are slightly lower than those estimated from the Cs-137 measurements. One possible explanation for this may be that sedimentation rates at these two sites have increased slightly over the past 35 years in response to changes in land use (Walling and Quine, 1991), and a general decline in the clearing and maintenance of the river channel and associated ditches and channels on the floodplain. For comparison, the CFCS Pb-210 lake sediment dating model was also applied to the two cores, and the resultant age–depth relationships are also depicted in Figure 3. The CFCS model gave sedimentation rates significantly higher than those estimated from the CICCS Pb-210 model and the Cs-137 method, and these higher values may reflect the influence of the remobilization of Pb-210 in the sediment profile by sediment mixing and the effect associated with the initial distribution of the direct atmospheric fallout input in surface sediment. The close relationship between the results derived from the CICCS model and those derived from the Cs-137 measurements suggests that the sedimentation rates estimated by the CICCS model are likely to be more reliable than those estimated by the CFCS model.

INVESTIGATING SPATIAL VARIATION OF SEDIMENTATION ON THE RIVER CULM FLOODPLAIN

Walling and He (1993) have previously reported the use of Cs-137 measurements to document spatial variation of medium-term (*c.* 35 years) sedimentation rates on the River Culm floodplain. The approach outlined above may also be used to obtain information concerning spatial variation of longer-term (*c.* 100 years) sedimentation rates on floodplains. Because the atmospheric fallout input of Pb-210 to the surface of a flood-

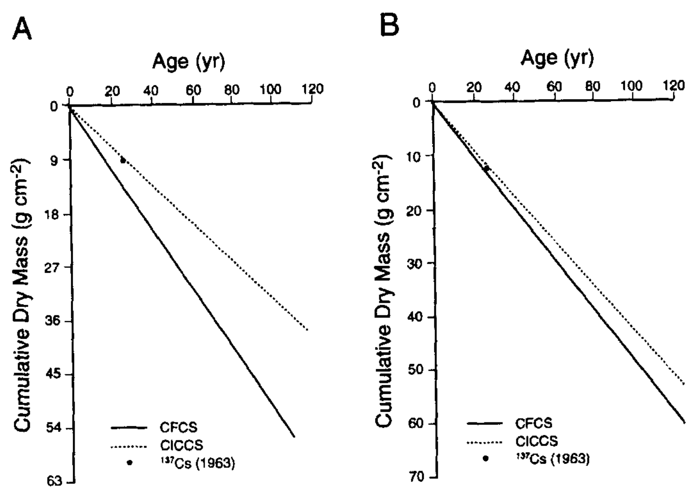

Figure 3. Comparison of the age–depth relationships derived from the CICCS floodplain Pb-210 model and the Pb-210 CFCS lake model and from the Cs-137 depth distribution for the two sediment cores collected from the Culm floodplain (A) and the Exe floodplain (B)

plain is primarily associated with wet fallout and may therefore be assumed to be relatively uniform spatially, the spatial variation of the total unsupported Pb-210 inventories, or of the catchment-derived unsupported Pb-210 inventories, will reflect the combined effect of spatial variation of sediment accumulation rates and of sediment composition (e.g. the grain size distribution). The latter effect will result in spatial variation in the unsupported Pb-210 concentrations in deposited sediment. Estimation of the catchment-derived unsupported Pb-210 concentrations in deposited sediment is an essential prerequisite for using catchment-derived unsupported Pb-210 inventories to derive sedimentation rates (see Equation 6).

The CICCS Pb-210 model has been used to investigate the spatial variation of sediment deposition on the River Culm floodplain near Silverton Mill over the past 100 years. A small area of the floodplain consisting of a meander bend near Silverton Mill, where the sectioned sediment core was taken, was chosen for this purpose (Figure 4A). This area comprises an elevated bank margin or natural levee surrounding a depression occupying the central part of the inner loop of the meander bend (Figure 4B). Analysis of a sediment core from the site suggests that the temporal variation of the grain size of the deposited sediment at this location has been insignificant over the past 100 years. Fifty-three bulk sediment cores over 70 cm long were collected from this area based on a 7 m × 7 m sampling grid. Surface sediment samples (*c.* 1 cm) were also collected adjacent to the coring positions. The core samples and surface samples were air-dried, ground and thoroughly mixed. Subsamples of the bulk cores were analysed for unsupported Pb-210 concentrations, and these values were used to calculate the unsupported Pb-210 inventories for the individual cores. The grain size composition of the surface sediment samples was also determined. Results of the analysis showed that the unsupported Pb-210 inventories for all the bulk cores were above the estimated local reference level, and the excess or catchment-derived unsupported Pb-210 inventories of the cores ranged from 50 to 830 $\mathrm{mBq\,cm^{-2}}$.

Spatial variation of excess unsupported Pb-210 within this area can be related to the processes of sediment accumulation and the sediment composition. The spatial pattern is shown in Figure 4C. The grain size composition of surface sediment samples has been assumed to be representative of the associated bulk cores. The initial concentration of unsupported Pb-210 in deposited sediment at each sampling point was estimated from the unsupported Pb-210 concentrations in overbank sediment deposits collected using sediment traps at various locations on the floodplain with appropriate grain size correction, based on the particle size composition of surface sediment collected from each sampling point. Equation 6 was then used to estimate the sediment deposition rate at that sampling point. The estimated sedimentation rates for the 53 cores vary from 0·07 to 0·59 $\mathrm{g\,cm^{-2}a^{-1}}$, and these values are again consistent with measurements of short-term deposition rates on the Culm floodplain obtained using sedimentation traps reported by Simm (1993). For a site at Columbjohn, 4 km downstream, with similar physical characteristics and a similar frequency of inundation, Simm reports sedimentation rates ranging between 0·09 and 0·80 $\mathrm{g\,cm^{-2}a^{-1}}$. Figure 5A depicts the spatial pattern of the estimated sedimentation rates at Silverton Mill. Highest sedimentation rates are found in the areas close to the channel on the downstream site of the meander bend. Although high sedimentation rates are generally associated with high excess unsupported Pb-210 inventories, the influence of the grain size composition of sediment on this relationship is also important. The spatial variation of sediment deposition rates thus identified reflects the complex interactions of the flow patterns and the sediment transport processes operating in this area. Walling and He (1993) have previously reported the distribution of Cs-137 inventories within this area and the spatial pattern of sedimentation estimated from the Cs-137 measurements. For comparison, this pattern is depicted in Figure 5B. The sedimentation rates estimated from the unsupported Pb-210 measurements are in close agreement with those estimated from the Cs-137 measurements, and the spatial patterns involved are very similar. Both the similarity of the results obtained from the unsupported Pb-210 measurements and Cs-137 measurements at this site and their general agreement with independent measurements of short-term rates of floodplain accretion obtained using sedimentation traps support the validity of the Pb-210 approach in estimating rates of floodplain sedimentation.

PERSPECTIVE

Fallout Pb-210 is deposited on floodplains through two pathways: direct atmospheric fallout associated with precipitation, and deposition, during overbank flood events, of catchment-derived fluvial suspended

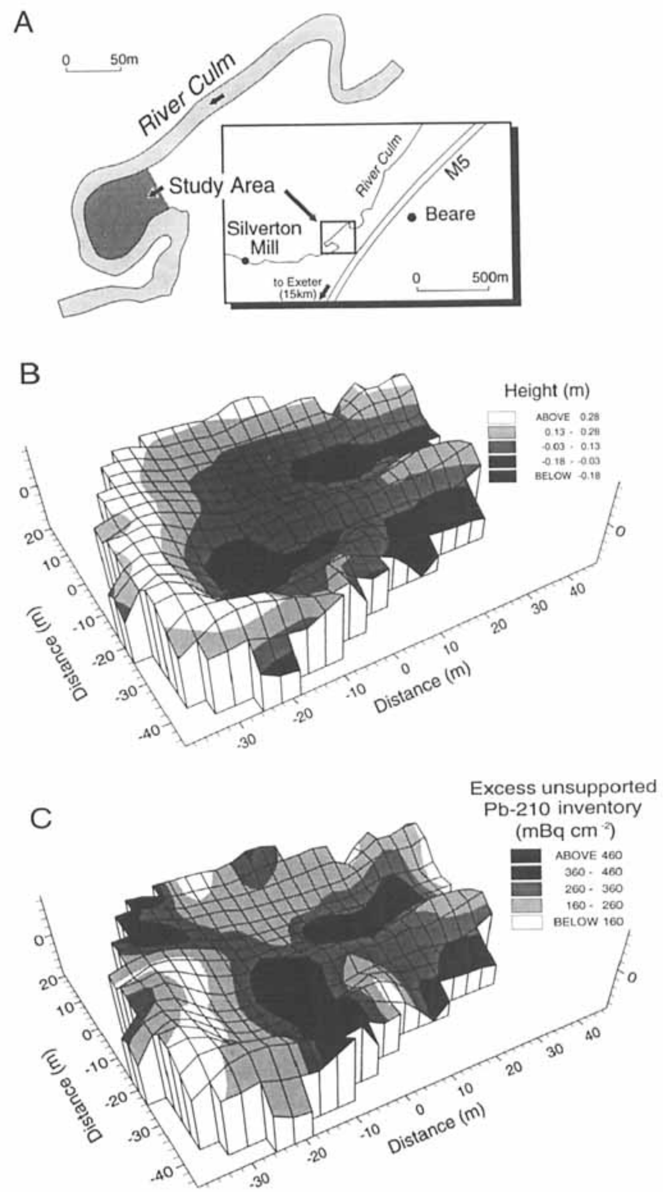

Figure 4. The location (A), topography (B) and spatial distribution of excess unsupported Pb-210 inventories (C) for the study reach of the River Culm floodplain near Silverton Mill

sediment containing unsupported Pb-210. The depth distribution of unsupported Pb-210 floodplain sediments is thus influenced by a number of factors, including the relative importance of the atmosphere-derived input, the initial distribution of the atmosphere-derived input in surface sediment, the magnitude and temporal variation of sedimentation rates, and the post-depositional remobilization of unsupported Pb-210 inputs. These factors need to be taken into consideration in any model employed to interpret unsupported Pb-210 profiles in floodplain sediments and in using such data for dating. The effects associated with the initial distribution of the atmospheric input and post-depositional redistribution of unsupported Pb-210 are likely to result in overestimates of sediment accumulation rates if the dating models developed for lake sediments are used. In places where sediment deposition rates and concentrations of catchment-derived unsupported Pb-210 are relatively high, sedimentation rates estimated using the CICCS model may be more

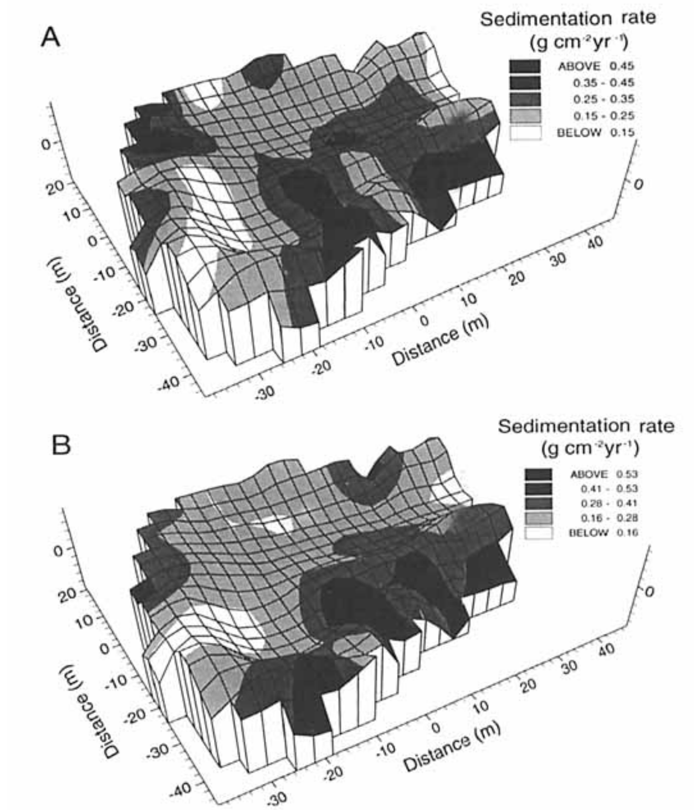

Figure 5. The spatial distribution of the sedimentation rates estimated using the CICCS Pb-210 model (A) and Cs-137 measurements (B) for the study area on the River Culm floodplain near Silverton Mill

reliable than those estimated using the other models, because the CICCS model avoids the difficulties introduced by sediment mixing. Application of the CICCS model to the two sediment cores collected from the floodplains of the Rivers Culm and Exe has supported its validity. The use of the catchment-related CICCS Pb-210 model for estimating floodplain sedimentation rates also represents a relatively rapid means for obtaining information about longer-term floodplain sedimentation rates, because only a single measurement of the unsupported Pb-210 content of the bulk core is required. This is important when a large number of cores are collected in order to document the spatial pattern of overbank sediment accumulation rates on a floodplain. Although the potential application of the CICCS model is limited by the assumption of a constant sedimentation rate and the fact that it therefore generates an estimate of the average sedimentation rate over the past 100 years, similar assumptions are necessarily invoked by most other approaches to estimating longer-term sedimentation rates based on datable levels and the assessment of the total deposition during a known period of time. The assumption of quasi-continuous sedimentation is likely to be generally acceptable for the floodplains of lowland rivers, but it may be checked for a particular site by inspection of a representative unsupported Pb-210 depth profile. The CICCS model has been used to investigate spatial variation of sedimentation on the floodplain of the River Culm near Silverton Mill. The magnitude and spatial pattern of the sedimentation rates derived using the CICCS Pb-210 model are closely similar to those estimated using the Cs-137 method, suggesting that sedimentation rates within this area over the past 100 years have been relatively constant.

Although in this paper emphasis has been placed on the potential for using measurements of the unsupported Pb-210 contents of floodplain sediments to obtain estimates of floodplain sedimentation over longer timescales than is possible with Cs-137, the two approaches should be viewed as complementary. In many

studies, potential will exist to measure both Cs-137 and unsupported Pb-210 activity simultaneously on the same cores, in order to estimate sedimentation rates over the medium (35 years) and longer term (100 years). Comparison of the results could provide a means of identifying changes in rates of sedimentation over the past 100 years (Walling and He, 1994). In addition, unsupported Pb-210 offers potential for use in areas where Cs-137 is likely to be of limited value. These areas include those parts of Europe which received significant amounts of Chernobyl fallout, which will complicate the interpretation of Cs-137 inventories, and those parts of the world, particularly equatorial regions, where available information on fallout rates indicates that total radiocaesium inventories are low and close to detection limits using conventional gamma spectrometry measurements.

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